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Technical Report No. 17

CIRCULATION NEAR THE WASHINGTON COAST

Office of Naval Research
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CIRCULATION NEAR THE WASHINGTON COAST

by

Harold A. Barnes and Robert G. Paquette

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Office of Naval Research
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January 1954



Richard H. Fleming
Executive Officer

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CIRCULATION NEAR THE WASHINGTON COAST

INTRODUCTION

The area covered in this paper is a section of the Northeast Pacific Ocean bordering the West Coast of North America between the parallels of 44° and 51° North and extending 600 miles seaward (Figure 1). The coast is mountainous and contributes considerable runoff to the sea from heavy precipitation in winter and the melting of the snow in early summer. Two concentrated sources of fresh water are the Strait of Juan de Fuca and the Columbia River which drain large inland areas. The Strait differs markedly from the river in that it is the mouth of a large tidal basin and is deeper than 100 fathoms for a considerable distance inshore. As a result of the tidal action, its effluent has been considerably altered by mixing with the cold deeper water.

The continental shelf, as measured by the 100-fathom contour, extends about 40 miles offshore near the Strait of Juan de Fuca and narrows to about 20 miles both northward and southward. Beyond the slope, depths increase gradually to about 2000 fathoms. A number of seamounts rise from this deeper water, but the bathymetry of only a few has been worked out in any detail.

The climate of the region is predominantly maritime with prevailing southwesterly onshore winds accompanied by heavy precipitation from autumn to spring. In summer, considerable air flow is from the northwest and north and little precipitation occurs.

The circulation of the Northeast Pacific is predominantly clockwise to latitude 40° North, giving way to counterclockwise south of 50° North (Sverdrup, Johnson and Fleming, 1946). The colder water along the northern periphery of the main easterly drift in mid-ocean, the so-called Aleutian or Subarctic Current, splits in an ill-defined zone well seaward from the coast near 45° North, both orientation and position of the zone of divergence varying with the season. The northerly arm, the Alaska Current, recurves through the Gulf of Alaska; and the southerly arm, the California Current, sets south well offshore at lower latitudes. Off the Washington and Oregon Coasts in winter, the Davidson Current feeds water northward inshore. The area studied, being an area of divergence, is characterized by weak and poorly defined currents which are easily influenced by temporally changing wind patterns and local bathymetric irregularities.

The measurements to be reported in this paper were carried out with the Research Vessel M.V. BROWN BLADE during seven offshore cruises in the spring and summer months of 1952 and 1953. Because of the anticipated variations of currents with time, determinations of circulation patterns by dynamic topographies were supplemented by use of the Geomagnetic-Electro-Kinetograph. It was quickly discovered that the latter instrument was measuring currents (or effects) very much greater than those from dynamic topographies, and showing a rotary variation with time. In recent cruises therefore, several time studies have been made to discover the nature of the rotary variations.

Further evidence of the reality of the rotary variations was obtained by direct current measurements from an anchor station on Cobb

Seamount, a seamount rising very sharply from 1500 fathoms depth to within 16 fathoms of the surface, and located approximately 270 miles west of the Washington Coast ($46^{\circ}45.5'N, 130^{\circ}46.3'W$). The results from two such time studies are presented in some detail.

Another sphere of activity has been a detailed investigation of the outflows of the Strait of Juan de Fuca and the Columbia River, particularly the latter. The outflow of the Columbia has been traced for over 200 miles seaward. The position and structure of this long plume of less saline water is of interest as an indicator of offshore circulation and mixing, and because of the possible influence it may exert in directing the salmon which migrate to and from the river.

The circulation near the coast of Vancouver Island and the mouth of the Strait of Juan de Fuca has been discussed by Tully (1938, 1941) on the basis of salinities and temperatures measured near the coast, often in shallow water. These measurements as well as those of Warner (1926) made from Swiftsure Lightship establish the direction of outflow of the Strait of Juan de Fuca as northwestward, very close and parallel to the coast of Vancouver Island. Tully further shows the accumulation of fresh water along the coast due to the prevailing southwesterly winds in spring and early summer, with a gradual transition to a condition of upwelling in a narrow band along the coast under influence of the northerly winds of late summer. He interprets the resulting dynamic topographies as representing northwesterly flows close to the coast in early summer and a reversal in direction in late summer. The latter flow, however, is overcome by the generally northwesterly outflow of the Strait of Juan de Fuca near the mouth of the Strait. Similar conclusions as to the seasonal shift in

currents were reached by Thompson and Van Cleve (1936) from drift bottle experiments commenced about 80 miles off the Canadian Coast. These authors also relate the change in direction of flow during the summer to a change in wind pattern. Some dynamic sections along the coasts of Washington and Oregon are presented by Sands (1937), but these are too few in number and too close to shore to correlate with the present work.

Farther offshore, the circulation off the Canadian Coast has been studied by Doe (1952) and Goodman and Thompson (1940) in two sections, from the Strait of Juan de Fuca to Dutch Harbor, and from the Strait of Juan de Fuca to Hawaii. Still farther offshore, the Carnegie Cruise VII (Fleming, 1945) established the gross structure of the eastward flowing Aleutian Current and the beginning of its separation into southeasterly and northeasterly branches. Two or more sections have also been made by Scripps Institution of Oceanography, the U. S. Fish and Wildlife Service, and the U. S. Navy Electronics Laboratory, but the results are unpublished. To the south, Scripps Institution of Oceanography have studied the coastal currents very intensively and their cruises have occasionally come as far north as the Columbia River. Thus the details of the circulation near the Washington Coast are little known.

With respect to the G.E.K., as used in areas of weak and poorly defined currents such as this, there is little published. The interpretation of the results as currents is in some question, as is the "K" factor. The apparently rotary current changes observed, although indicated by von Arx (1950), have not been carefully analyzed, probably because in areas of high currents they are relatively less important. Oceanographers at Scripps Institution of Oceanography are known to be working on this problem.

For analysis of the rotary current changes in the deep sea, one must turn to the direct measurements made from anchored vessels, the BLAKE in West Indian waters (Pillsbury, 1891), the MICHAEL SARS (Holland-Hansen, 1930), the METEOR (Defant, 1932), the ALTAIR (Defant, 1940), and the ARMAUER HANSEN (Ekman, 1953). In all of these, the uncertainties due to the motion of the anchored vessels weakens the validity of the conclusions. However, rotary current changes do occur and these changes apparently contain components of tidal and inertial periods as well as random fluctuations. The existence of rotary currents of tidal period in shallower water is well established, and Gustafson and Kullenberg (1936) have demonstrated an excellent example of inertial rotations in the Baltic.

WATER PROPERTIES AND CIRCULATION

As others have suggested, the horizontal gradients of temperature and salinity may be generalized in two representations, one for spring and early summer and one for late summer. The winter conditions have not been studied. Figures 2 and 3 show the horizontal distribution of surface temperature and surface salinity in April-May, 1953, the data having been smoothed to eliminate local fluctuations. The piling up of warm surface water along the coast of Vancouver Island is evident.

Figures 4 and 5 show the conditions in July, 1952. Here the breakdown of spring conditions is just beginning to appear. The water which earlier increased in temperature essentially up to the coast is now showing a wide band of somewhat cooler water near the coast. The effect is more marked if vertical sections of temperature are plotted,

demonstrating the decrease in thickness of the surface water layer on approaching the coast. Close to the mouth of the Strait of Juan de Fuca, the effect is accentuated at the surface probably because of the mixing processes of tidal flow as well as the tendency of upwelling deeper water to appear far within the Strait.

Figures 6 and 7 (smoothed somewhat) show the conditions in September, 1953, farther south. Although not completely comparable with the above data because of the different areas covered, there is still superficial evidence of upwelling in the region near the mouth of the Strait of Juan de Fuca. Along the Washington Coast south of the Strait, the subsurface temperature structure indicates the presence of upwelling which, however, does not reach the surface because of a blanketing layer of less saline water. This is especially so in the vicinity of the Columbia River mouth where the surface waters flowing seaward are rapidly replaced by river effluent. Along the Oregon Coast south of the Columbia, low temperatures characteristic of upwelling are again apparent at the surface.

Figures 6 and 7 also show the first results of a detailed study of the Columbia River outflow. The plume of water having a salinity less than $32.0^{\circ}/\text{oo}$ is seen to extend over 200 miles to the southwest. Associated with the lower salinity is a somewhat higher temperature. The position of the wake stream is in itself evidence of the generally southerly set of the currents in this region during the summer. At the velocities indicated by the dynamic topography for the general area, the time required for the water to travel to the outer limits of the $32^{\circ}/\text{oo}$ isosal is of the order of one to two months, and hence the position of this limit establishes a minimum value for the integrated currents for at least this period.

The processes of mixing in the wake stream have not yet been examined. However, there is some interest attached to the abrupt change in salinity gradient seaward of the $31.0^{\circ}/\text{oo}$ isosal. In essentially all of the area between this and the next isosal, the surface salinities are greater than $31.5^{\circ}/\text{oo}$ and mostly greater than $31.7^{\circ}/\text{oo}$.

The dynamic topographies within 300 miles of the coast have been quite consistent in all the cruises analyzed. Since only Cruise No. 7 in July, 1952, went as far offshore as 600 miles, data from this cruise are combined with a composite of all the others to obtain a generalized diagram for the area which is presented as Figure 8. The curves south of 46° - $30'$ are based principally upon data from Cruise No. 9 in early September, 1952.

Appearing generally in all cruises are the lower dynamic heights to the west of about 130°W , corresponding to northerly or northeasterly flows of 5 cm/sec or less. Some changes in gradient occur in different months but the general picture is little altered except that the contours seem to turn more nearly northward in the early summer, as would be expected from the meteorological conditions. Also appearing in all the data is evidence for a deflection southward of northeasterly flowing streamlines in the area between 128° and 130°W and 47° to 49° - $30'\text{N}$. The data of Cruise No. 9 indicate that this flow continues southward along the Washington Coast and is probably responsible for carrying the Columbia River water southward. These results are consistent with those of Doe (1952).

G.E.K. RESULTS AND TIME STUDIES

Early in the investigations, it was discovered that apparent currents measured hourly by means of the G.E.K. along a cruise track showed continual changes in direction and magnitude, suggesting the rotary changes of tidal period observed at lightships. These currents typically had peak values of 15 - 20 cm/sec and occasionally as high as 35 cm/sec, the correction factor "K" for the G.E.K. being taken as unity. To be contrasted with these are the velocities below 5 cm/sec determined from the dynamic heights. Tidal periods could be found in the data by harmonic analysis, but the amplitudes were only about one-fifth as great as the observed peaks. Later it was discovered that inertial periods were present, with amplitudes of the same magnitude or somewhat greater than those of tidal period. The inertial period in this area is approximately 16 hours. The harmonic analyses of these data were interpreted with some reservations due to the fact that the ship was rapidly changing position and to the evident existence of apparently random fluctuations of considerable magnitude.

In order to derive the residual non-fluctuating currents in this situation, the data have been calculated as 48-hour running means, 48 hours being the least common multiple of 16 and 12 hours. If tidal and inertial constituents are present, they should disappear in the averages together with the greater part of those of shorter and random periods. This is admittedly a rather brutal treatment, as any fluctuations in the residual current are severely smoothed thereby. However, it has served for the preliminary investigations.

A serious disadvantage is the fact that the ends of a continuous series of observations may be approached within only 24 hours by averaged results, and hence any lengthy break in continuity of the data may leave large gaps in the results. Twenty-four hour groupings also have been tried and are found to remove most of the fluctuations and leave smaller gaps. It is preferred to use 48-hour means where possible, however, since the results will be less ambiguous.

The results of such a treatment to the data of Cruise No. 7 are shown in Figure 9. The large gap in the data on the northern leg of the cruise is due to the break in continuity occasioned by a short storm. Twenty-four hour means, however, show the residual currents setting south to southwest throughout most of the northern leg with velocities of the order of 5 to 8 cm/sec. A comparison with Figure 8 shows some similarity of G.E.K. means to the dynamic heights along 48° - $30'$ N but none whatsoever along 50° - $30'$ N. The current pattern is also internally inconsistent, requiring the existence of a region of convergence within the area surveyed, an improbable situation. It appears evident therefore that the G.E.K., in this region, does not always measure the long-term average flows associated with the distribution of mass. The converse might be true in regions where stronger currents are found.

It is postulated therefore that the currents measured are shallow wind-driven currents of short duration. To test this hypothesis, average wind vectors have been plotted along the course. There is reasonable correspondence along 48° - $30'$ assuming the resulting flow to be 45° to the right of the wind and lagging it by a few hours. In the northwest corner of the survey, there appears to be an inconsistency. However, the

northwest storm which appeared two days later at about 130° W longitude may already have been driving water well ahead of it. Along 50° - 30° , the agreement with 24-hour average currents (not shown) is good.

These results showed the necessity of making time studies with the G.E.K. The first studies, begun in June, 1952, were about one day in length and were made by steaming back and forth over an 8- to 16-mile course, obtaining G.E.K. fixes enroute. Hydrographic stations to 1,000 meters depth were occupied at intervals of 2 to 12 hours in the several experiments in an attempt to correlate the results with the dynamic heights. Rotary changes in current direction were readily demonstrated, but twenty-four hour periods are too short for effective harmonic analysis. Two experiments of 3 to 4 days' duration were therefore made in June and August, 1953, Cruises No. 29 and 31, respectively.

In Cruise No. 29, the ship steamed backward and forward two hours' run on reciprocal headings, taking G.E.K. fixes every hour together with other data. Positions were fixed frequently by Loran, and hydrographic stations were occupied about every 12 hours. Some failures in equipment being used for corollary measurements caused several undesirably large gaps in the data, but the results are only a little less consistent than those to be presented below.

In Cruise No. 31, the cruise plan was modified, as suggested by Mr. Joseph Reid of Scripps Institution of Oceanography, so that the ship steamed squares on the cardinal compass headings, each side being approximately 7 minutes' run. Thus a fix is obtained every 7 minutes, there being some interdependence in the measurements because each station enters into two fixes and two zero determinations. The data obtained

experiments of this type in which he has simultaneously followed a freely drifting buoy (personal communication). An attempt to do this with an improvised buoy and drag was abandoned after the buoy lost its drag and was itself nearly lost at night during a radar failure.

The results of this experiment have been expressed as north and east components of velocity and are presented in Figure 10. K has been assumed to be unity and corrections have been made for electrode droop. The results are surprisingly consistent and have given rise to a renewed belief in the reality of G.E.K. measurements. The 16-hour inertial period is evident by visual inspection. Much of the distortion is due to other components, principally the semidiurnal. Some smoothing has been practiced but there is difficulty in deciding which fluctuations may be real and which due to experimental uncertainty. Due to the interdependence of separate fixes, errors often appear symmetrically in alternate or adjacent points. Moreover, in some cases the record can not be interpreted more accurately than several tenths of a millivolt.

In correlation with this experiment, an anchor station was occupied for the preceding three and one-half days atop Cobb Seamount (See Figure 8). Here currents were measured at 20 meters depth with an Ekman current meter every 30 minutes, and temperature structures were measured hourly by bathythermograph. Bathythermograms were also obtained hourly during the time study with the G.E.K. Three hydrographic stations were occupied at corners of a 30-mile square about the seamount to obtain dynamic heights for comparison. The time study with the G.E.K. was performed in depths ranging from 1,500 to 500 fathoms and between 30 and 15 miles northwest of the seamount. The ship drifted south during the period.

The direct current measurements also show rotary changes containing tidal and inertial components. The basic periods are less well defined because of the motions of the ship, but these motions are small compared to those of a ship anchored in deep water. It is assumed in these two experiments that there should be some similarity in the currents on a sharp isolated seamount to those in the adjacent deep water. On the other hand, considerable distortion near the seamount would not be surprising.

The results of harmonic analysis are given in Table I, for both the direct measurements and the G.E.K. Only the 16- and 12-hour components are considered of primary importance, but the higher harmonics are presented to suggest the magnitude of the amplitudes which could result from random data in a series of this length. The contribution of each constituent is assumed to be expressed in the form

$$v_n = V_n \cos (\theta - K_1)$$

$$v_e = V_e \cos (\theta - K_2)$$

where \underline{v}_n and \underline{v}_e are the instantaneous values of the north and east components of velocity, \underline{V}_n and \underline{V}_e are the corresponding amplitudes, θ is the time angle of the constituent and \underline{K}_1 and \underline{K}_2 are the local epochs, the negative of the conventional phase angle, the origin of time being the time of local lunar transit on the first day of the anchor station.

If $K_2 - K_1$ expressed as an angle less than 180° is positive, rotation of the current vector with time is clockwise. In particular, if $K_2 - K_1 = 90^\circ$ and $\underline{V}_n = \underline{V}_e$, the current hodograph for the constituent is a circle. Theoretically, circular changes are to be expected in the inertial component and generally elliptical changes in the tidal component.

It is evident that most of the motion is accounted for by inertial and semidiurnal constituents, the former preponderating. The diurnal constituent is probably of significant magnitude, but the others are questionable. The phase difference between north and east components in these three constituents corresponds to clockwise rotations, as would be expected from the deflecting force of the earth's rotation. In the inertial constituent, it is very nearly 90° for both the direct measurements and the G.E.K. In the G.E.K. results, the two amplitudes are essentially the same, which satisfies the condition for circular rotation. Further deductions from the phase relations will be attempted at a later date. The amplitude of the semidiurnal constituent on Cobb Seamount is about 15 per cent less than the G.E.K. results, which is the same as the change in the mean tidal range at Astoria during the two periods. The change in the inertial component may arise from an increase in average wind velocity from about 8 to 20 knots over the same period.

The results of the time study in June, 1953, are shown in Table II. Although the amplitudes are smaller, the relative importance of the 16- and 12-hour constituents is supported. This experiment was carried out at $48^\circ-02'N$, $130^\circ-29'W$; and by chance during the time study, the ship drifted over and charted a new seamount rising to a least depth of 280 fathoms. This shallowing of the water may have had some effect upon the G.E.K.

The possibility exists that internal waves of tidal and inertial period give rise to the currents or effects measured by the G.E.K. This has been investigated by a study of the bathythermograms taken to a depth of 450 feet during the time study of Cruise No. 31. Internal waves occur

with amplitudes of the order of 25 feet but with periods poorly defined. Visual examination suggests six-hour and two-hour periods rather than those of twelve or sixteen hours. It is felt therefore that these internal waves are not a determining influence on the G.E.K. results, but that they possibly account for some of the aberrations and short-period constituents.

In Table III, the average residual current calculated from the three time studies is compared with the dynamic topographies and with the approximate drift of the ship as determined by deviations from the courses run, measured by loran fixes. In Cruise No. 29, the G.E.K. compares well with the drift of the ship but not with the dynamic topographies. This was in a period of light winds in which the ship might be expected to move with the water. In Cruise No. 31, there is little agreement, possibly because the winds averaged 20 knots from the north. However, the direct current measurements compare favorably with the dynamic topographies close to the seamount. Farther away, the velocity and direction derived from the topographies are extremely uncertain and are not shown. It seems well established therefore that the rotary changes observed by the G.E.K. in deep water have their counterpart in the direct measurements of currents.

CONCLUSIONS AND SUMMARY

The water circulation off the coasts of Vancouver Island, Washington and Oregon in late spring and summer has been studied by means of dynamic topographies and the G.E.K. A picture is presented which fills a previously existing gap in the information for the central area. The

relatively flat dynamic topography is especially sensitive to transient conditions and experimental error. Nevertheless, the topographies consistently show a weak northeasterly circulation at 5 cm/sec or less, part of which is deflected southward off Vancouver Island to continue along the coast past 45° North. This circulation pattern is consistent with previous work in the adjoining areas, and with the assumed divergence of the Aleutian Current beginning well offshore around 45° North.

The G.E.K. has been shown to measure apparent currents which rotate in direction and fluctuate in intensity. The peak flows are of the order of 20-35 cm/sec which is several times greater than the net flows. The rotations contain semidiurnal and inertial constituents, the latter predominating.

A time study in direct measurement of currents on Cobb Seamount, 270 miles offshore, has been compared with a similar time study with the G.E.K. in the adjoining deep water. Harmonic analysis of the North and East components of velocity has produced amplitudes of 7-11 cm/sec for the semidiurnal constituents. The relative differences are the same as the corresponding changes in the mean tidal range at Astoria during the period of the measurements. The amplitudes of the inertial constituent were 9 and 13 cm/sec in one case and 22.5 cm/sec in the other, a difference ascribed to an abrupt change in wind velocity. Another time study with the G.E.K. showed similar results, but smaller amplitudes. The combined results suggest that the currents being measured by the G.E.K. are real. This conclusion is supported by the published results of current measurements at several deep-sea anchor stations which show similar variations.

The net currents obtained by averaging the G.E.K. results show little correspondence with those indicated by dynamic topographies. The former probably represent short-term surface currents due to the wind, whereas the dynamic topographies represent integrated effects over longer periods.

In conclusion, it is suggested that progress in the interpretation of currents in this area requires a better insight into the cause and nature of the transient currents. The G.E.K. should be useful in these studies, but must be further evaluated in terms of direct measurements.

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TABLE I

HARMONIC ANALYSES OF CURRENTS
DIRECT MEASUREMENTS AND G.E.K. COMPARED

4 - 11 August 1953

Period, solar hours	24.8		16		12.4		8.3		6.2		4.1	
	Dir.	GFK	Dir.	GFK	Dir.	GFK	Dir.	GFK	Dir.	GFK	Dir.	GFK
Amplitude cm/sec	N. Comp.	2.6	3.0	12.6	22.4	7.6	3.4	1.1	1.3	2.5	0.9	0.8
	E. Comp.	2.6	2.5	9.1	22.6	10.9	2.0	2.6	0.5	2.3	2.0	1.3
Local Epoch, λ^* , in degrees	N. Comp.	167	192	338	14	332	319	120	292	109	182	318
	E. Comp.	295	279	68	102	85	112	124	78	177	69	157

* The constituents are expressed as the cosines, and λ^* is the positive angle measured from the time of local lunar transit on 4 August to the time of constituent maximum.

TABLE II

HARMONIC ANALYSIS OF CURRENTS

by G.E.K

7 - 10 June 1953

Period, solar hours		24	6	12
Amplitude cm/sec	N. Comp	2.3	5.4	4.9
	E. Comp.	3.7	5.6	4.6
Local Epoch*, χ , in degrees	N. Comp.	171	194	245
	E. Comp.	234	274	274

* The constituents are expressed as cosines, and χ is the positive angle measured from the time of local lunar transit on 7 June to the time of constituent maximum.

TABLE III

COMPARISON OF NET VELOCITIES

by

DIRECT MEASUREMENT, G.E.K., AND DYNAMIC TOPOGRAPHIES

		Velocity cm/sec	Set °T
<u>Cruise No. 29</u>			
G.E.K.		6.6	130
Dynamic Topography		3	055
Drift of Ship		5	155
<u>Cruise No. 31</u>			
Direct Measurement		4.5	095
G.E.K.		3.6	270
Dynamic Topography	Cobb Seamount	10	100
	G.E.K. Position	?	?
Drift of Ship		10	173

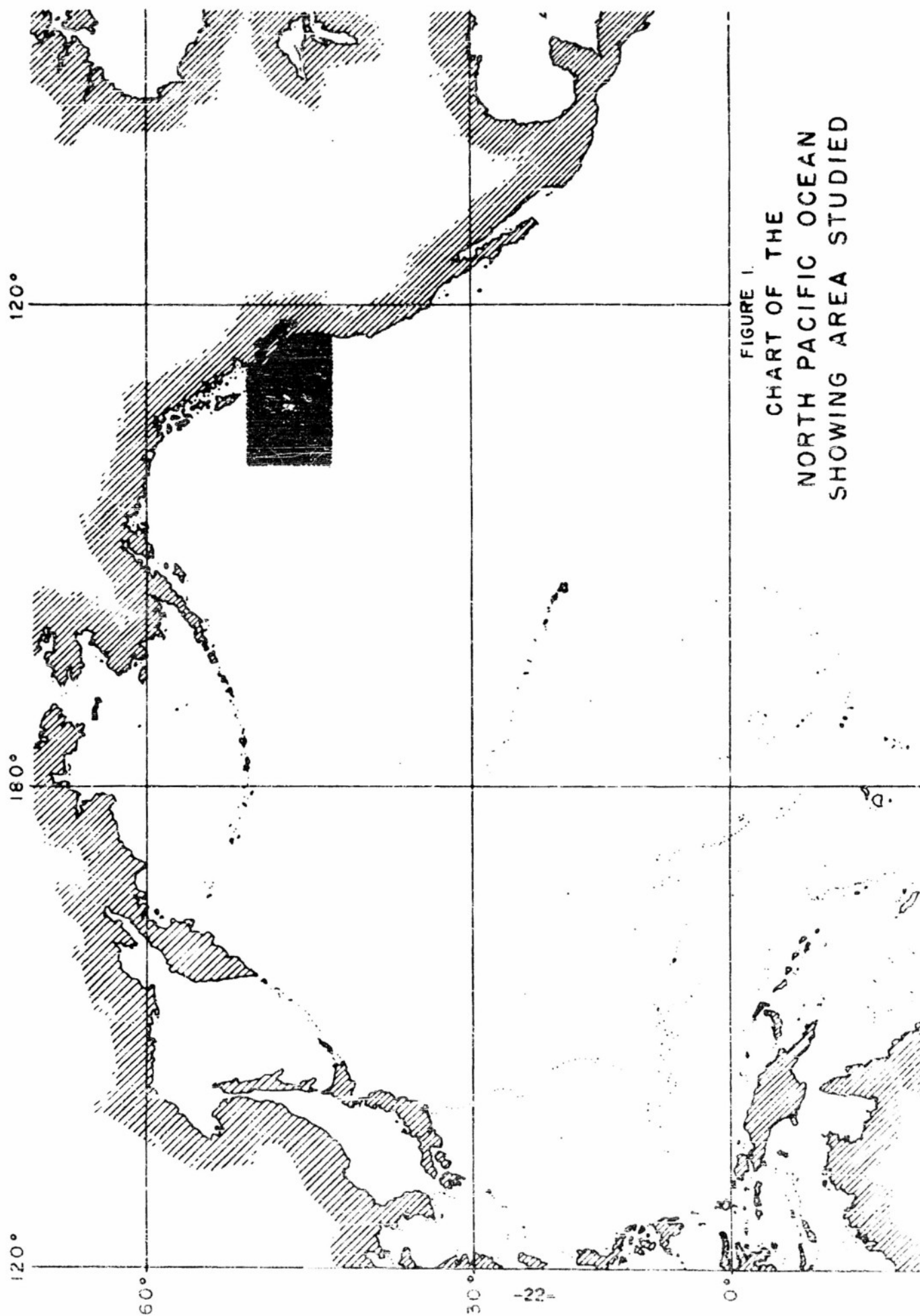
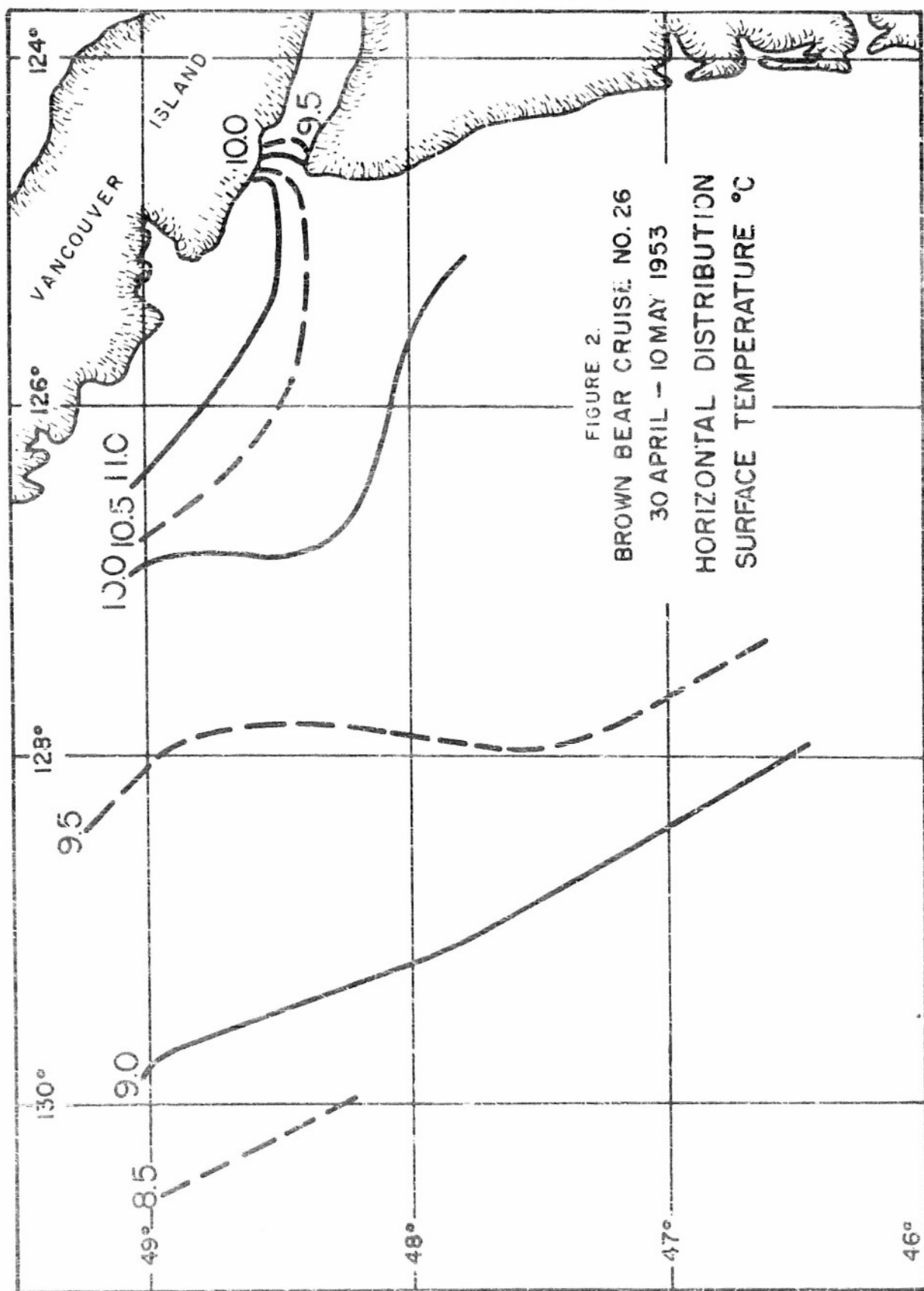
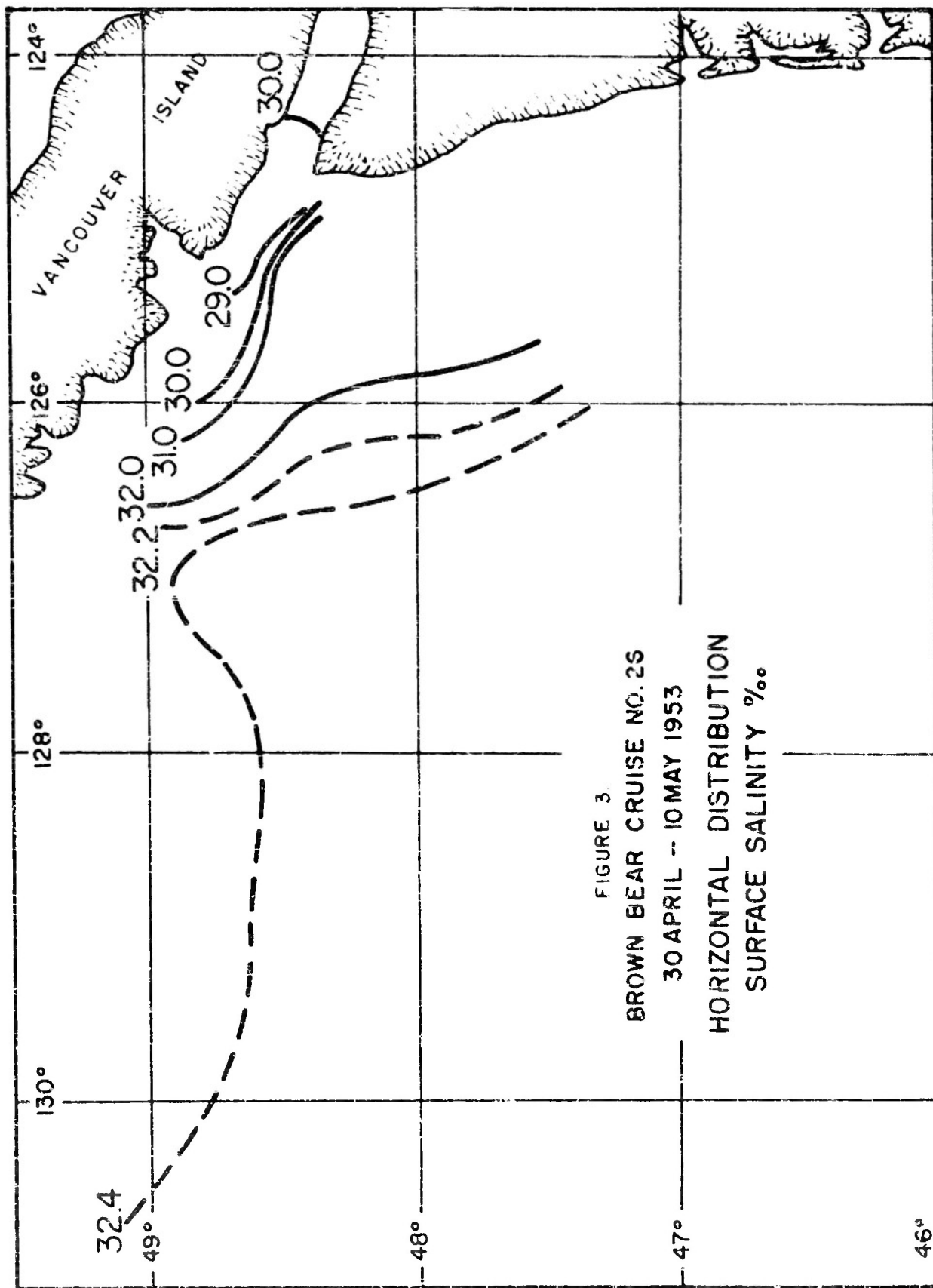


FIGURE 1.
CHART OF THE
NORTH PACIFIC OCEAN
SHOWING AREA STUDIED





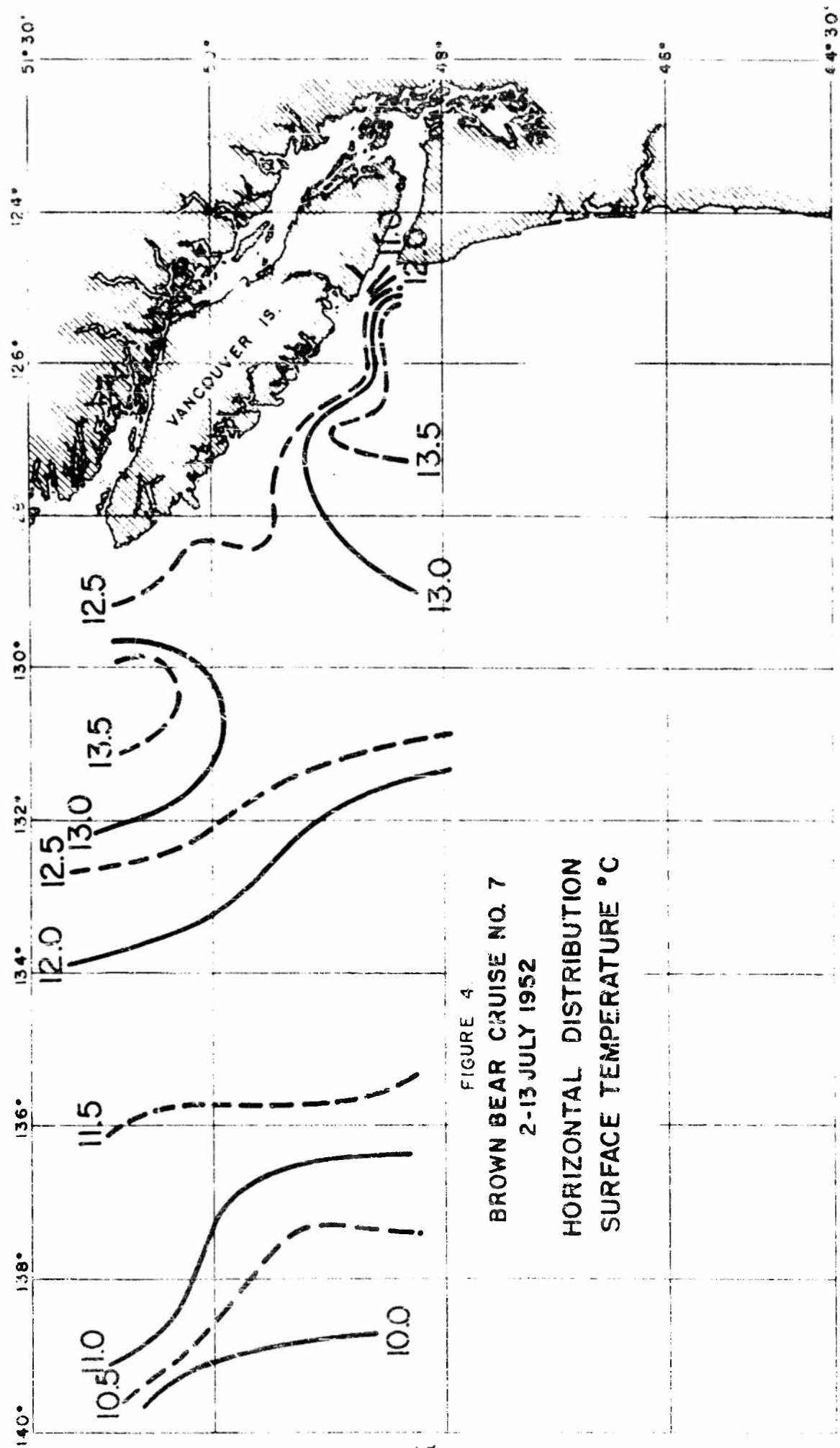


FIGURE 4
BROWN BEAR CRUISE NO. 7
2-13 JULY 1952
HORIZONTAL DISTRIBUTION
SURFACE TEMPERATURE °C

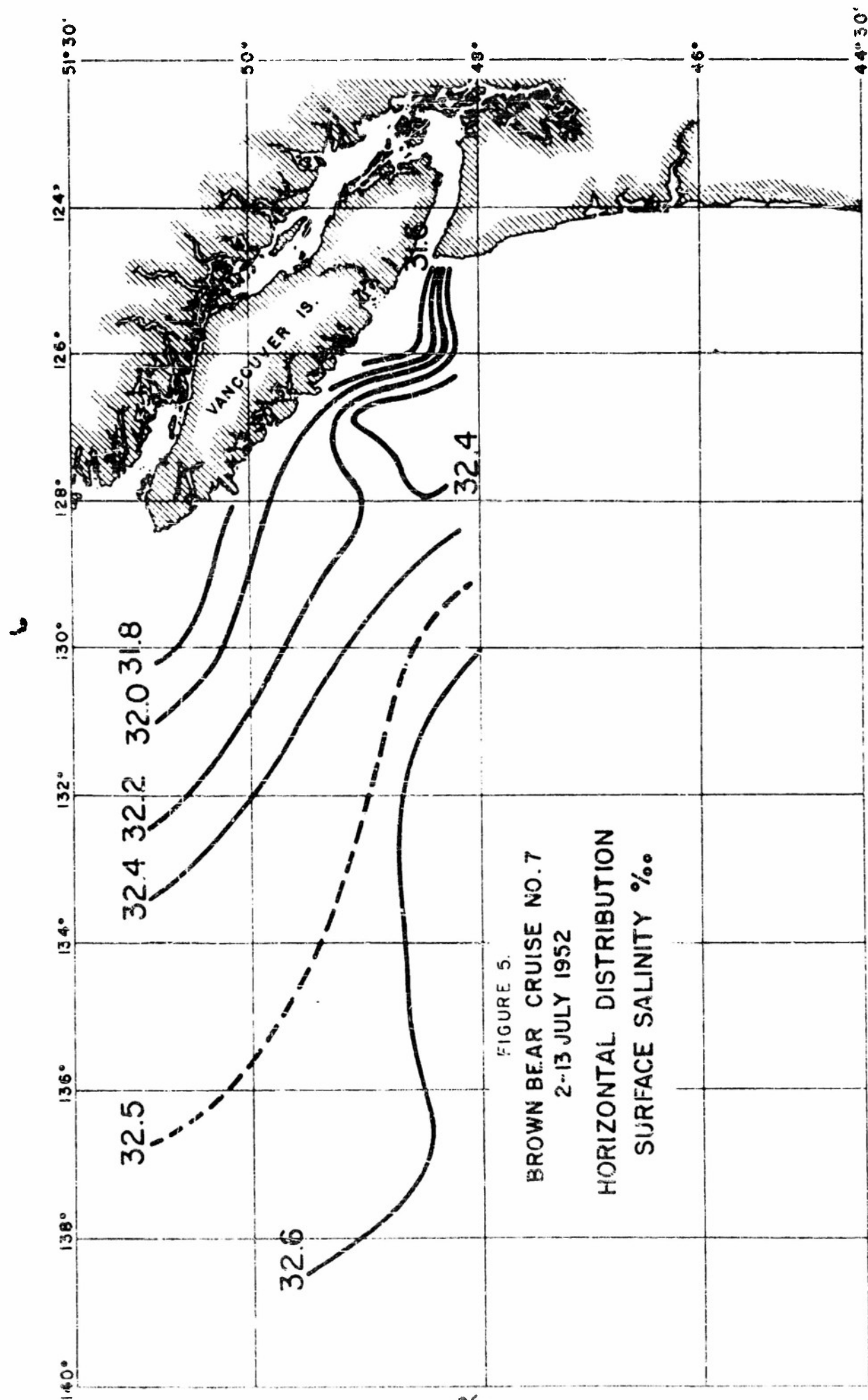
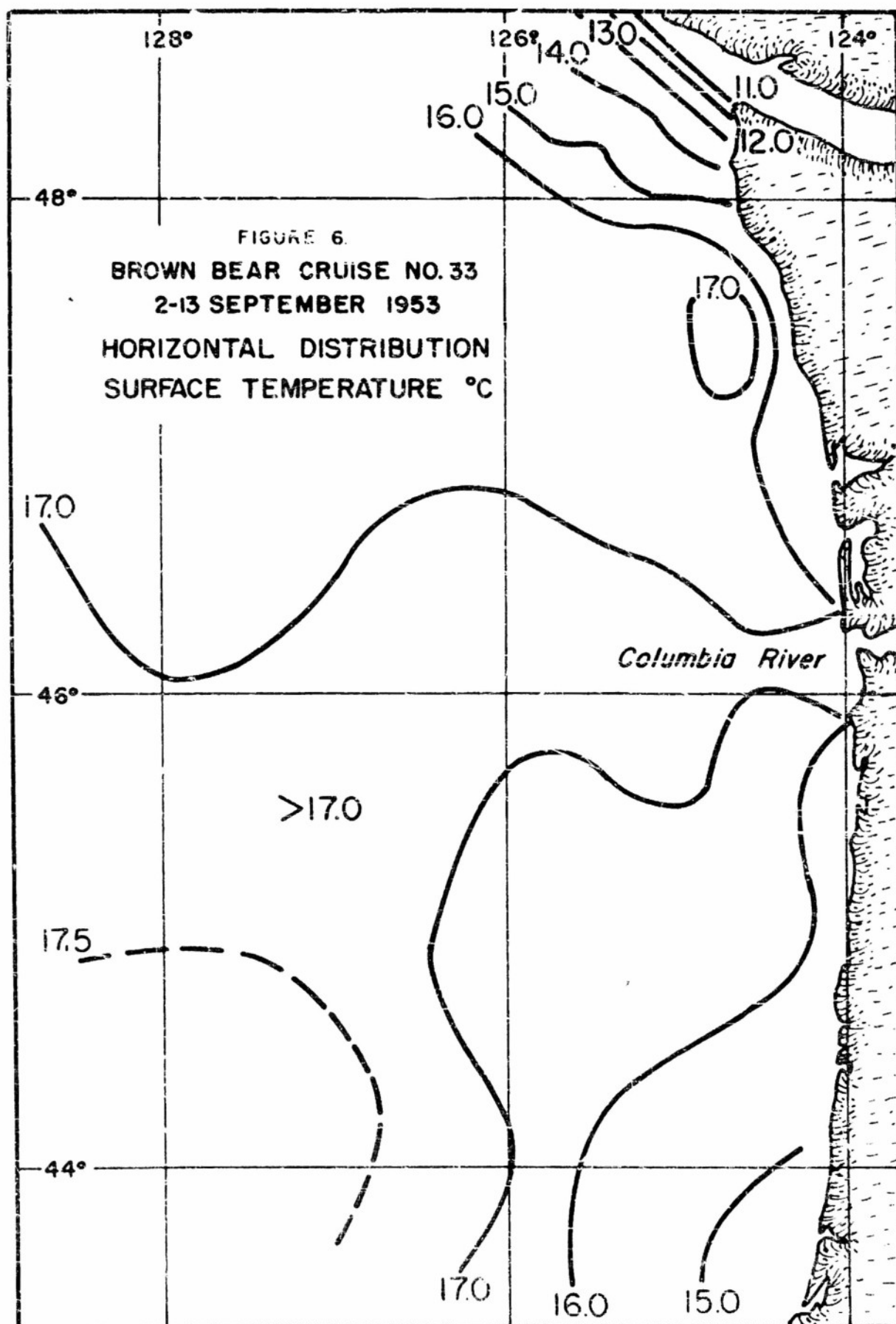
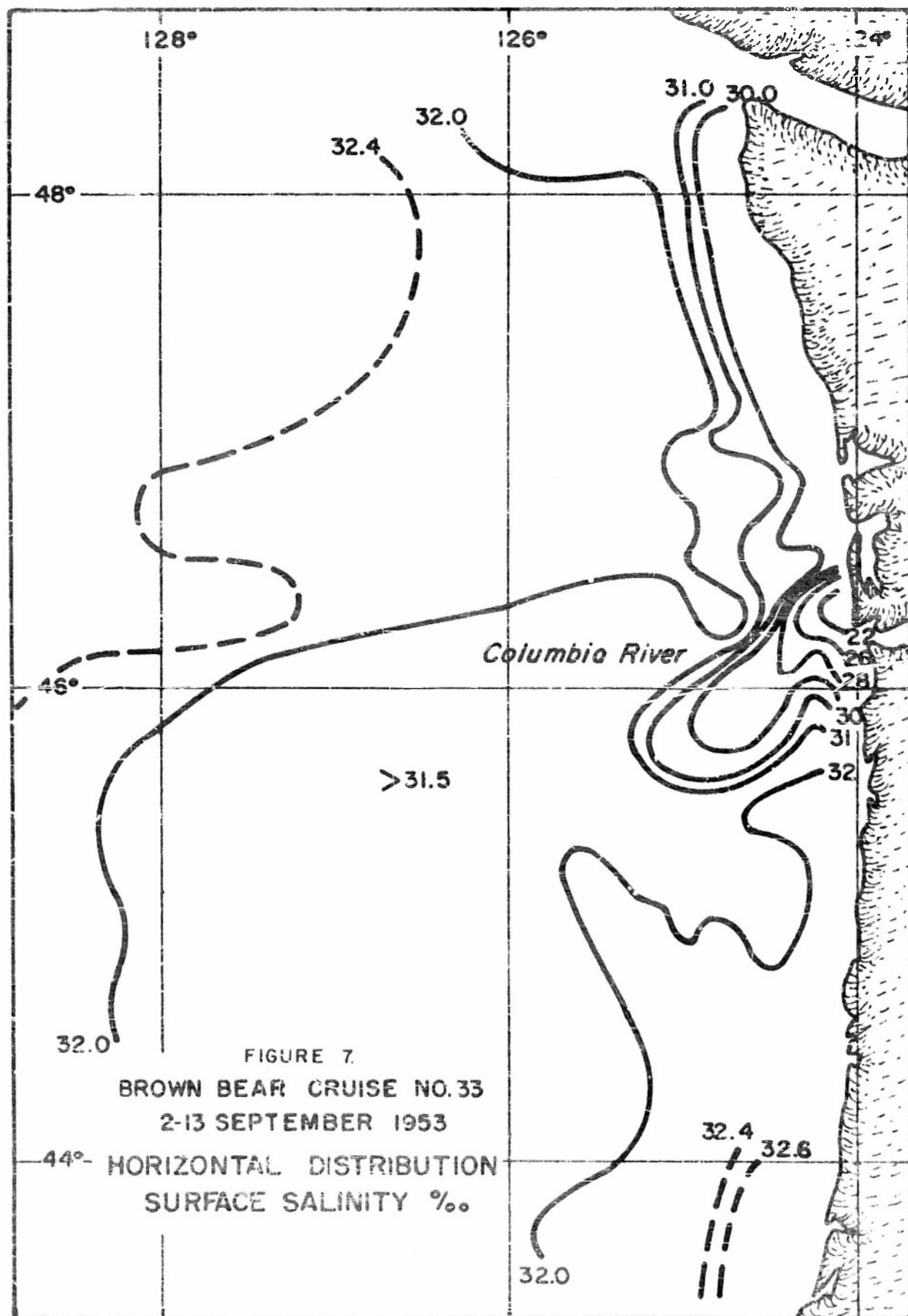
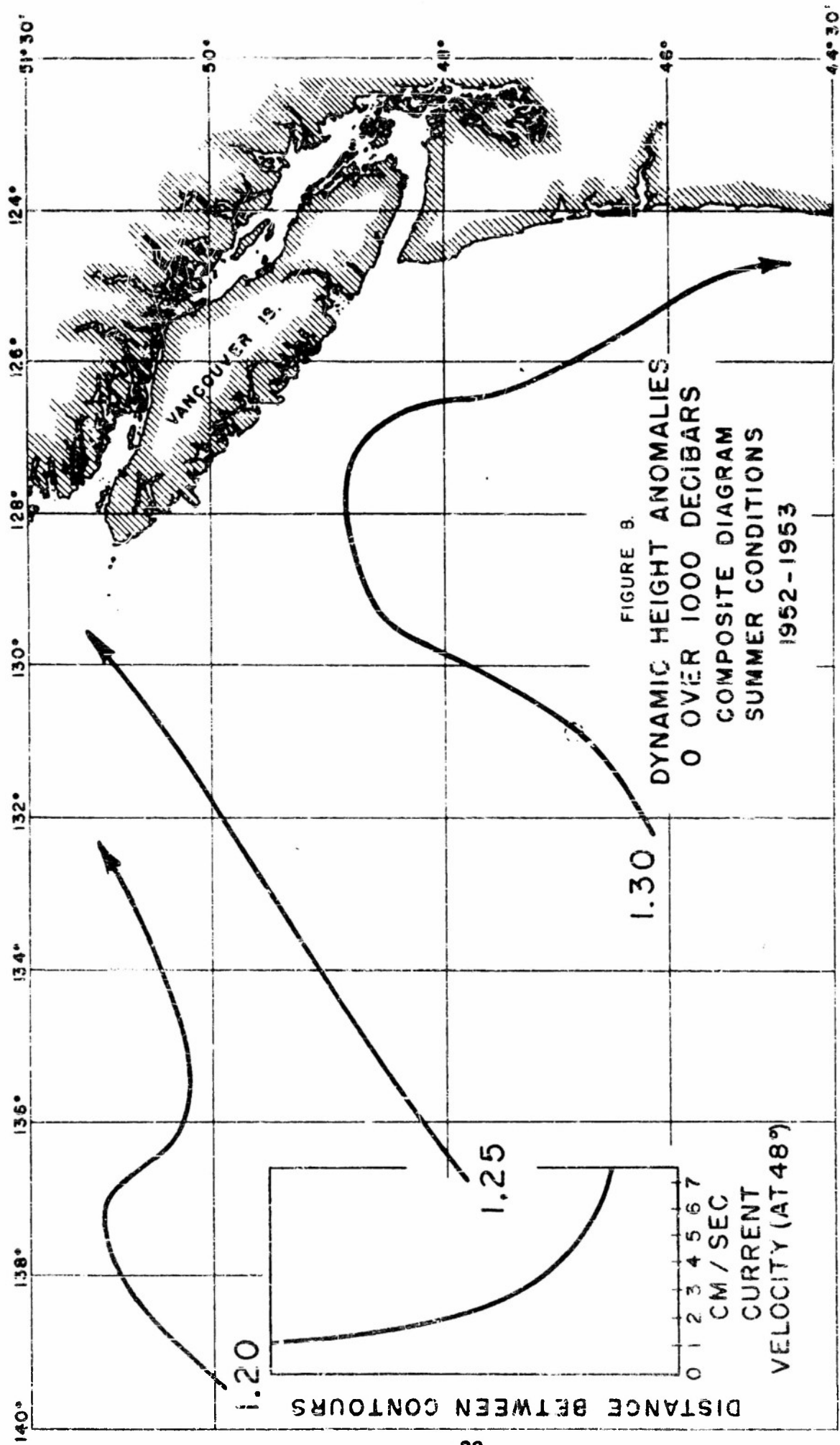


FIGURE 5.
BROWN BEAR CRUISE NO. 7
2-13 JULY 1952
HORIZONTAL DISTRIBUTION
SURFACE SALINITY ‰







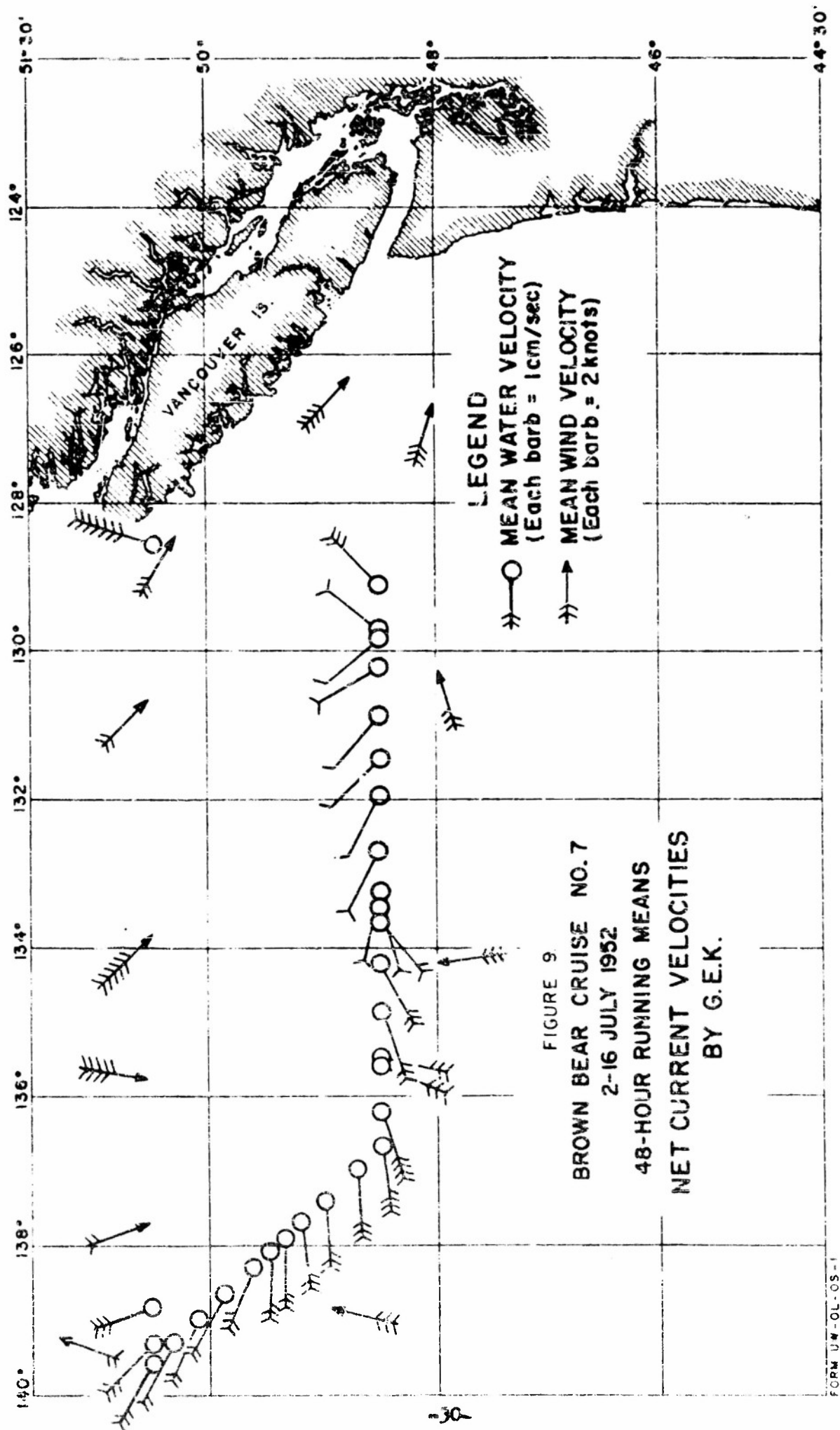
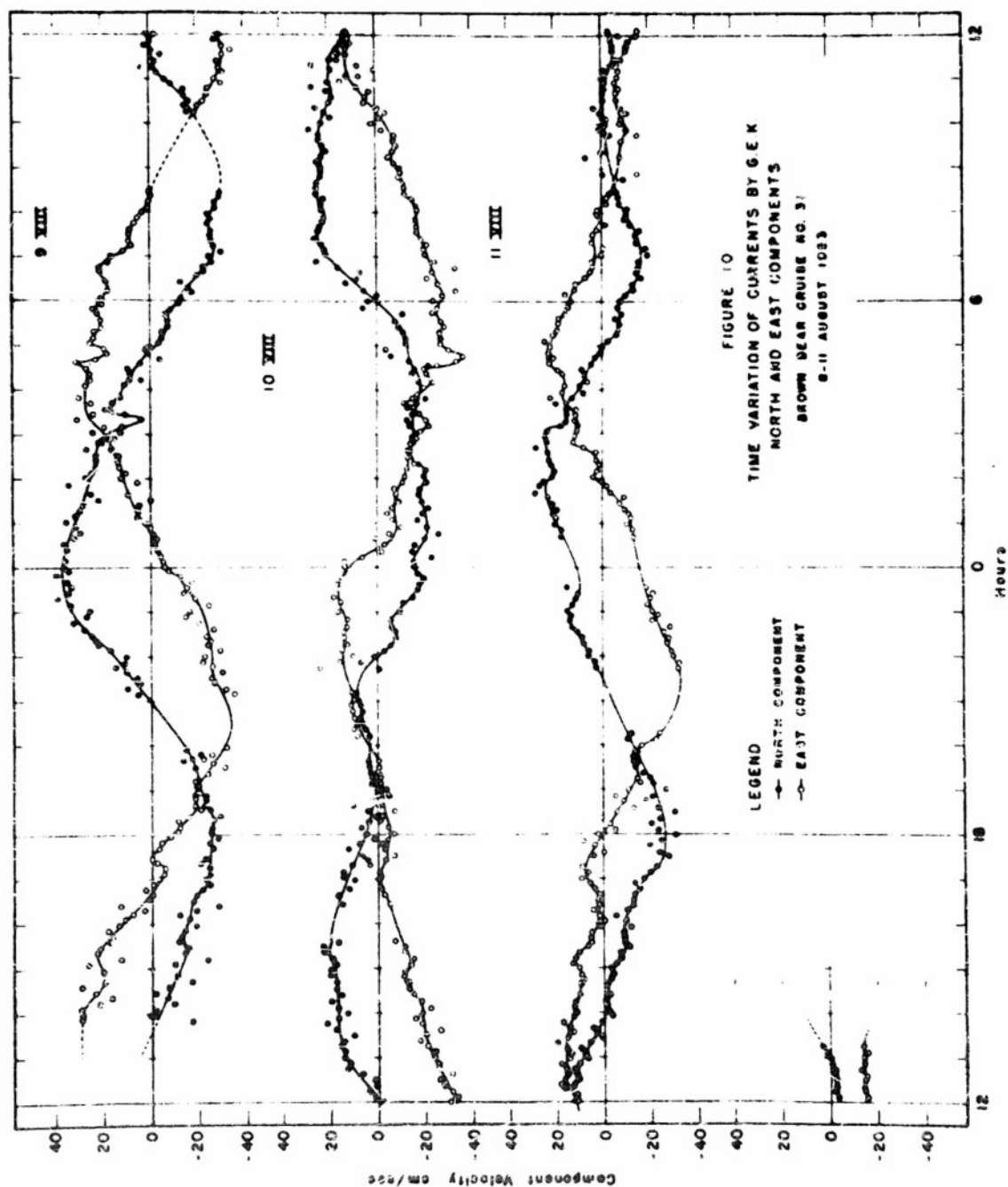


FIGURE 9
 BROWN BEAR CRUISE NO. 7
 2-16 JULY 1952
 48-HOUR RUNNING MEANS
 NET CURRENT VELOCITIES
 BY G.E.K.



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